REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE - August 1999	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE

Mobile Communication Network with Directive/Adaptive Antennas

5. FUNDING NUMBERS

DAAH04-96-1-0315

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 34526.12-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

The final report is composed of two parts:
1. The first six months report which outlines the problems studied, and
2. Abstracts of publications summarizing research over the remaining term of the contract.

There were brief periods of time during which support was given to students working on impulse radio, a novel technology of significant interest to the US Army.

19991103 076

14. SUBJECT TERMS			15. NUMBER OF PAGES
			16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

DTIC QUALITY INSPECTED 4

Mobile Communication Network with Directive/Adaptive Antennas

GRANT DAAH04-96-1-0315

FINAL TECHNICAL REPORT

1 July 1996 - 30 June, 1999

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PROGRESS DURING THE FIRST SIX MONTHS OF GRANT DAAH04-96-1-0315

One problem that we proposed to study was the effectiveness of double-ended search algorithms, and their dependence on antenna and signal parameters. When directive antennas are available at both the transmitter and receiver, a degree of time synchronization is required to achieve linking with a minimum of radio exposure, i.e., the transmitting antenna beam and the receiving beams must be pointed at each other. Since accurate universal time information is available from a GPS receiver when four or more satellites are in view, it appears possible to minimize radio exposure/maximize power efficiency by dividing time into slots for link initiating purposes, e.g., with {transmission south, listen north} occurring in one specified time slot, {transmission east, listen west} in another specified time slot, etc. Once a link handshake has been achieved, the antennas can maintain their orientation throughout the duration of the communication. Without a reasonably accurate time source, link initiation would become a more lengthy and risky process. We have spent the initial six months of this contract on two aspects of the above task, namely link acquisition and signal interception during the acquisition process.

Link Acquisition with Directive Antennas

We have developed a reasonable and detailed statistical model for the link acquisition process as a function of antenna characteristics and transmitter powers. All noise and interference, after despreading in the receiver, is assumed to be white and Gaussian for detection modeling purposes. We assume that the link initiating transmitter has an *a priori* probability density for the location of the intended receiver. After each unsuccessful attempt at link transmission, the transmitter computes an *a posteriori* density for the intended receiver location, based on the immediately prior location probability density, the transmitted signal power and directional antenna properties during the attempt, and the observed signal levels during the corresponding handshake interval. We have implemented this process in software and can graphically display the results.

Items that we have not embedded in the simulation include the effects of the terrain on the propagation process and of multipath on the beam-pointing algorithm. We don't yet have adequate models for these effects, and to some extent we expect them to be dependent on particular properties of the communication system.

Our current objective is to optimize the directive antenna search algorithm as much as possible while attempting to keep both the complexity of the algorithm and the radio exposure of the transmitter as small as possible.

Interception during Acquisition

In a digital battlefield environment, an interceptor tries to detect the presence and the coming direction of the link signals transmitted by a communication initiating node. The intercept process is focused on the time period when a communication initiating node transmits link signals to its destination node for link setup. The reason for this is that after a link is established, the pair of communication nodes can cooperate on strategies to avoid being intercepted, e.g., they can use different and longer spreading codes, narrow down their

antenna beam widths and reduce their transmission power, etc. Thus we concentrate on intercept strategies during the link setup period.

For each (quantized) direction, we applied Bayes theorem to calculate the *a posteriori* probability that the initiator lies in that direction. In this process, the *a posteriori* probability is averaged over all choices of the possible search directions and power levels that the initiating communication node might use. The objective is that the interceptor should determine the next search direction so as to minimize the search time, given its current state of knowledge. We have investigated three different algorithms based upon the *a posteriori* probabilities of the direction of the initiating node computed after the most recent search: (1) steer the interceptor's antenna beam in the direction that currently is most likely, (2) steer the interceptor's antenna beam in the direction which over the most recent observation has the largest increase in likelihood, and (3) find the direction with maximum likelihood increase over the previous observation interval and then put a null of the interceptor's antenna beam in that direction. The search stops when the *a posteriori* probability of a particular direction of the initiating node exceeds a preset threshold, and the initiating node is declared to be located in that direction.

In the computer experiments that we have performed to date, the third algorithm is the fastest one because, when a direction is nulled, the *a posteriori* probability of that direction will be quickly diminished if it is not the true direction of initiating node. We have software displays of the sequence of angle probability densities that occurs when exercising each of these algorithms.

MANUSCRIPTS SUBMITTED/PUBLISHED under GRANT DAAH04-96-1-0315

- "An Optimal Link Power Set for a Mobile Communication Network with Directive/Adaptive Antennas", by Tien-Yow Liu & Robert A. Scholtz, presented at *MILCOM '97*, Monterey, CA, October 1997.

- *3 copies sent 12/97.*

A B S T R A C T

The mobile communication (non-centralized) network with directive/adaptive antennas plays an important role in the digital battlefield in the future. Every user in this non-centralized network has directive or adaptive antennas for transmitting and receiving communication signals. One of the most important design problems in this network is that the communication link between a communication transmitter (CT) and a communication receiver (CR) is not detected by an unfriendly interceptor (UI). Without knowing the exact location of CR, a CT needs to search for the CR in different directional bins (each has angle equal to antenna beam width) at different time slots. An ascending search power algorithm between a CT and a CR is developed such that the probability of intercept is minimized when the CT searches for CR in each directional bin. Instead of using maximum transmission power level, a CT first uses the lowest transmission power level to search for the CR

in the directional bin which has the highest probability of CR location. If the first search attempt is unsuccessful, then CT uses the second lowest transmission power level to search for CR in the same direction, etc. The optimal link power levels in every directional bin are obtained by minimizing the probability of intercept when a CT searches for a CR using the above protocol. The optimal solutions are analyzed by approximating the probability of link and intercept as unit step functions, and two examples are presented.

- "Strategies for Minimizing the Intercept Time in a Mobile Communication Network with Directive/Adaptive Antennas," by Jung-Hyun Oh & Robert A. Scholtz, presented at *MILCOM '97*, Monterey, CA, October 1997.

- *3 copies sent 12/97.*

ABSTRACT

For hostile communication environments, a non-centralized mobile communication network with directive/adaptive antennas and Global Positioning Systems (GPS) has been proposed for the purpose of minimizing the radio exposure and making it difficult for an interceptor to detect the signals. The directive antennas, however, cause a spatial search process to find the direction of the intended receiver and setup a link for communication. During this link setup process, an interceptor has the opportunity to observe the transmitter's main antenna beam. This paper investigates the strategies for minimizing the interceptor time when the interceptor uses a single beam antenna to detect the signal presence and find the transmitter direction. We adopt the Bayes' rule to recursively update the directional *a posteriori* probabilities, which leads to a sequential decision problem. Four different algorithms to determine the next search direction based on the updated probabilities are compared through simulations.

This paper was selected and received the Fred Ellersick Award for the Best Unclassified Paper at MILCOM '97.

- "A Link Activation Protocol for A Mobile Communication Network with Directive/Adaptive Antennas", by Tien-Yow Liu & Robert A. Scholtz presented at *MILCOM '97*, Monterey, CA, October 1997.

- *3 copies sent 12/97.*

ABSTRACT

A non-centralized (non-cellular) mobile communication network with directive/adaptive antennas is proposed. Every node uses directive/adaptive antennas for transmitting and receiving communication signals. The spatial and temporal synchronization of transmitting and receiving antenna beams are accomplished by employing Global Positioning System (GPS) information and a double-ended spatial search algorithm. The communication link

setup between a communication transmitter (CT) and a communication receiver (CR) depends on the successes of both forward and reverse links. A CR uses a non-coherent matched filter receiver and a signal power estimator to determine accept/reject of the incoming signals from CT in AWGN channels. Without knowing the exact location of CR, a CT has to search for the CR in different directions using different transmission power level. In a hostile environment, a search algorithm is developed by maximizing the probability of linking without intercept for a CT in every search trial. Updating the statistical information of CR location by a CT after every search also reduces the uncertainty of CR location and the search time.

- J.-H. Oh and R. A. Scholtz, "Optimal Interception and Direction Finding of Signals in a Mobile Communication Network with Directive Antennas," *Proc. Military Comm. Conf.*, Monterey CA, November 2-5, 1998.

- *3 copies sent 12/98.*

ABSTRACT

For hostile communication environments, non-centralized mobile communication network with directive/adaptive antennas and Global Positioning System (GPS) has been proposed for the purpose of minimizing the radio exposure and making it difficult for an interceptor to detect the signals. This paper investigates the interceptor's search for the direction-of-arrival (DOA) of the transmitting signal by the method of sequential test and decision when the interceptor also uses a single beam directive antenna. We adopt the dynamic programming algorithm to obtain the optimal action and test to minimize the weighted sum of mean observation number and the average decision error.

We also come up with the one-step-to-look-ahead policy and the maximum *a posteriori* policy that always chooses the direction with the maximum *a posteriori* probability and the corresponding costs by building new dynamic programmings. Simplifying an antenna beam shape, the numerical results are presented and compared among policies for a single beam antenna system.

- "Multiple-Access with Time Hopping and Block Waveform PPM Modulation" Fernando Ramirez-Mireles and Robert A. Scholtz, *Proc. Military Comm. Conf.*, Monterey CA, November 2-5, 1998..

- *3 copies sent 8/99.*

ABSTRACT

The use of time-hopped block waveform encoding PPM signals sets for multiple access communications is studied. The multiple access performance is analyzed in terms of the number of users supported by the system for a given bit error rate and bit transmission rate. The analysis shows that this technique is potentially able to provide multiple-access communications with a combined transmission capacity of over 500 Megabits per second at bit error rates in the range 10^{-4} to 10^{-8} using receivers of moderate complexity.

- Tien-Yow Liu and R. A. Scholtz, "Link Search Algorithms for a Spread-Spectrum Mobile Communication Network with Directive/Adaptive Antennas," *IEEE Conf. on Communications*, June 1998.

- *3 copies sent 12/98.*

ABSTRACT

A non-centralized fully distributed mobile communication network with directive or adaptive antennas is proposed. Every node uses directive or adaptive antennas for transmitting and receiving communication signals. The spatial and temporal synchronization of transmitting and receiving antenna beams is accomplished by employing the Global Positioning System (GPS) information and a double-ended spatial search algorithm. This research focuses on the problem of how a communication transmitter (CT) establishes the communication link with a communication receiver (CR). Two link search algorithms, (1) a sequential ascending search power algorithm using an optimal set of link power levels and (2) a sequential Bayesian search algorithm using Bayes rule to update the CR location information, for additive white Gaussian noise (AWGN) channels, are proposed for a CT to search for its intended CR. A probability of interference, used as performance measurement for link search algorithms, is defined as the ratio of expected number of interfering event to the total number of the un-intended CRs per transmission. Examples and asymptotic analyses of the two link search algorithms employing a realistic antenna pattern are presented in this paper.

- J.-H. Oh and R. A. Scholtz, "Optimal Sequential Detection of DOA in a Mobile Communication Network with Directive/Adaptive Antennas," submitted to *IEEE Transactions on Communications*.

- *1 copy sent 12/98.*

ABSTRACT

For hostile communication environments, non-centralized mobile communication network with directive/adaptive antennas and Global Positioning System (GPS) has been proposed for the purpose of minimizing the radio exposure and making it difficult for an interceptor to detect the signals. This paper investigates the interceptor's search for the direction-of-arrival (DOA) of the transmitting signal by the method of sequential test and decision when the interceptor also uses a single beam or a double beam directive antenna. We adopt the dynamic programming algorithm to obtain the optimal action and test to minimize an objective cost function which can be set up in many different ways according to different criteria. In this paper, we consider two objective cost functions: the weighted sum of mean observation number and the average decision error, and mean observation number alone with a constraint on the decision error.

It is proved that the successive mappping makes some costs converge to the optimal cost and there exists a stationary optimal policy. To deal with the unknown parameter, the

received signal-to-noise ratio (SNR), we propose to take an average when we use a single beam antenna, and estimate it when a double beam antenna is available.

We also come up with the one-step-look-ahead policy and the maximum *a posteriori* policy that always chooses the direction with the maximum *a posteriori* probability and the corresponding costs by building new dynamic programmings.

Simplifying an antenna beam shape, the numerical results are presented and compared for different policies and criteria for such cases as a single beam antenna with known and unknown SNR, and a double beam antenna with a maximum likelihood SNR estimator.

- Tien-Yow Liu and R. A. Scholtz, "Link Activation Protocols for a Mobile Communication Network with Directive/Adaptive Antennas," submitted to *IEEE Transactions on Communications.*

- *1 copy sent 12/98.*

ABSTRACT

A non-centralized fully distributed mobile communication network with directive/adaptive antennas is proposed in this paper. The spatial and temporal synchronization of transmitting and receiving antenna beams is accomplished by employing the Global Positioning System information and a synchronized spatial search algorithm. The link setup between a communication transmitter (CT) and a communication receiver (CR) depends on the success of both forward and reverse links. A two-way communication link protocol is defined as a basic agreement for the link activation in the network. Two link search algorithms, (1) a sequential ascending search power algorithm (SASPA) using an optimal set of link power levels and (2) a sequential Bayesian search algorithm (SBSA) using Bayes rule to update the CR location information, for additive white Gaussian noise channels, are proposed for use in a hostile communication environment. The optimal SBSA can be obtained by using dynamic programming but the computational complexity is unfeasibly high. The experimental results in which the CT uses a non-coherent matched filter receiver for spread-spectrum code acquisition and the unfriendly interceptor uses a wide-band energy detector for both link search algorithms are presented.

PH.D. THESES COMPLETED DURING THIS PERIOD

- **Tien-Yow Liu,** "Link Activation Protocols for a Mobile Mobile Communication Network with Directive/Adaptive Antennas," Ph.D. Dissertation, May 1998, University of Southern California.

- *1 copy sent 12/98.*

A B S T R A C T

A non-centralized fully distributed mobile communication network with directive or adaptive antennas is proposed in this thesis. Every node uses directive or adaptive antennas for transmitting and receiving communication signals. The spatial and temporal synchronization of transmitting and receiving antenna beams is accomplished by employing the Global Positioning System information and a double-ended spatial search algorithm. This research focusses on the problem of how a communication transmitter (CT) establishes the communication link with a communication receiver (CR). The communication link setup between a CT and a CR depends on the successes of both forward and reverse links. A two-way communication link protocol is defined as a basic agreement for the link activation in the network. Two link search algorithms, (1) a sequential ascending search power algorithm (SASPA) using an optimal set of link power levels and (2) a sequential Bayesian search algorithm (SBSA) using Bayes rule to update the CR location information, for additive white Gaussian noise channels, are proposed for a CT to search for its intended CR in both hostile and friendly communication environments. The optimal SBSA can be obtained by using dynamic programming but the computational complexity is unfeasibly high. All the link protocols, search algorithms and theories developed in this thesis are general, and can be applied to any realistic antenna patterns and to any particular receiver using any type of digital modulations. The experimental results that the CT uses a non-coherent matched filter receiver for spread-spectrum code acquisition and the unfriendly interceptor uses a wide-band energy detector for both link search algorithms are presented in this thesis.

- **Fernando Ramirez, Mireles,** "Multiple-Access with Ultra-Wideband Impulse Radio Modulation Using Spread Spectrum Time-Hopping and Block Waveform Pulse Position Modulated Signals, Ph.D. Dissertation, August 1998, University of Southern California.

- *1 copy sent 12/98.*

ABSTRACT

Impulse radio (IR) is an ultra-wideband (UWB) modulation that uses waveforms that consist of trains of time-shifted subnanosecond pulses. Data is transmitted using pulse position modulation at a rate of many pulses per symbol. Multiple access capability is achieved using spread spectrum time hopping. Impulse radio promises to be a viable technique to build relatively simple and low-cost, low-power transceivers that can be used for short range, high speed multiple-access communications over the multipath indoor wireless channel.

In [8] the single-user multiple-access performance of IR assuming free space propagation conditions and additive white Gaussian noise (AWGN) was studied. The analysis assumed that binary pulse-position-modulated (PPM) signals based on binary time-shift-keyed (TSK) modulation are detected using a correlation receiver. The analysis in [8] is quite similar to that for code-division multiple-access made in [26] and is based on the fact that both designs use single-channel correlation receivers for phase-coherent detection of the bit waveform.

In this dissertation we generalize the ideas in [8] to investigate the use of block-waveform signals to increase the data transmission rate supported by the system without degrading the multiple-access performance for a given number of users, or to increase the number of users supported by the system for a given multiple-access performance and bit transmission rate. More specifically, we present three M-ary block-coded PPM signal designs and analyze the multiple-access performance of IR using these PPM signals. We also discuss some of the tradeoffs between performance and receiver complexity. Using this idealized analysis, numerical examples given in chapter 5 show that IR modulation is potentially able to support hundreds of users, each transmitting at a rate over a Megabit per second at bit error rates as low as 10^{-8}. Similarly, it is shown that IR is potentially able to support thousands of users, each transmitting at a rate about ten Kilobits per second at bit error rates in the order of 10^{-4}. In either case, the combined transmission rates give a transmission capacity of ovr 500 Megabits per second using receivers of moderate complexity.

We also include an assessment of the performance of IR modulation in the presence of dense multipath (no multiple-access interference is considered in this assessment). Numerical results in chapter 6 show that for a particular set of $M = 4$ signals and symbol error probability of 10^{-3}, the performance in the presence of multipath using a mismatched Rake receiver with $K = 10$ fingers is, on average, just 3 dB worse than performance in the absence of multipath using a correlation receiver.

- **Joung-Heon Oh**, "Sequential Detection of DOA in a Mobile Communication Network with Directive/Adaptive Antennas" Ph.D. Dissertation, December 1998, University of Southern California.

- *1 copy sent 8/99.*

A B S T R A C T

For hostile communication environments, a non-centralized mobile communication network with directive/adaptive antennas and Global Positioning System (GPS) has been proposed for the purpose of minimizing the radio exposure and making it difficult for an interceptor to detect the signals. This thesis investigates the interceptor's search for the direction-of-arrival (DOA) of the transmitting signal by means of a sequential test and decision when the interceptor also uses a single beam or a double beam directive antenna. Bayes' rule is adopted to recursively update the directional *a posteriori* probabilities of the transmitter direction, which leads to a sequential decision problem. After making an observation and updating the probability distribution of the DOA, the interceptor decides either the direction it will use for the next search (action) or it stops searching and makes a decision (test).

The dynamic programming algorithm is adopted to obtain the optimal action and test to minimize an objective cost function. This can be set up in many different ways according to different criteria. In this thesis, two objective cost functions are considered: (1) the weighted sum of mean observation number and the average decision error probability and (2) the mean observation number alone with a constraint on the decision error probability.

It is proved that the successive mapping makes some costs converge to the optimal cost and that there exists a stationary optimal policy. To deal with the unknown parameter, the received signal-to-noise ratio (SNR), we propose to take an average when a single beam antenna is used, and to estimate it when a double beam antenna is available.

The costs of a one-step-look-ahead policy and the maximum *a posteriori* policy are also computed by the dynamic programming algorithm.

Numerical solutions are calculated with a simplified antenna beam shape and they are compared for different policies and different antenna systems. Simulations show that the optimal policy obtained from the simplified model is a good candidate for the original system.

PERSONNEL SUPPORTED

FACULTY

Robert Scholtz   Principal Investigator

RESEARCH ASSISTANTS

Tien-Yow Liu	Part-time, September 1996	August 1998
Fernando Ramirez	Part-time, Jan 1, 1998	Jan. 15, 1998
Chrisikos, George	Part-time, March 1998	May 1998
Lee, Joon-Yong	Part-time, September 1998	June 1999
Li, Huiwen	Part-time, September 1998	January 1999
Corrada, Carlos Jeronimo	Part-time, September 1998	September 1998
Joungheon Oh	Part-time, September 1996	August 1998

TRAVEL

- Dr. Scholtz traveled to Tucson, Arizona, 27-30 April, 1997 to attend and participate in paper presentations at the *Comm. Theory Workshop.*

- Dr. Scholtz traveled to Phoenix, Arizona, 4-7 May, 1997 to attend and participate in the *Vehicular Technology Conference.*

- Dr. Scholtz travelled to Batimore, Maryland, 18-20 June, 1997, to attend as an invited speaker and panel chairman at the *ARO/ARL Workshop on Spread Spectrum for Tactical Mobile Wireless Communications.*

- Dr. Scholtz travelled to Quantico, Virginia October 15-16, 1997, to attend and deliver a presentation at the *Ultrawideband Tactical Electronic Device Demonstration and review.*

- Dr. Scholtz traveled to Huntsville, AL and Atlanta, GA, 121-24 June, 1998, to attend the *IEEE APS Symposium* and have technical talks on related reseach at Time-Domain.

- Dr. Scholtz traveled to San Jose, CA, on November 5, 1998 to attend the *FCC UWB NOI* Meeting at Interval Research Corporation in Palo Alto.